ORNL Fusion Program

Presented at the

FY2005 Budget Planning Meeting

Office of Fusion Energy Science

Stanley Milora

Director

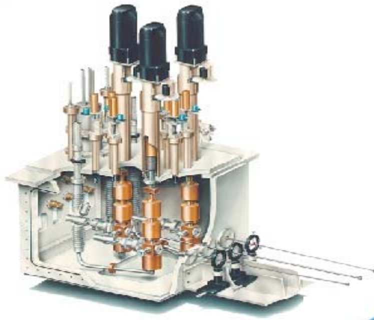
Fusion Energy Division

Oak Ridge National Laboratory

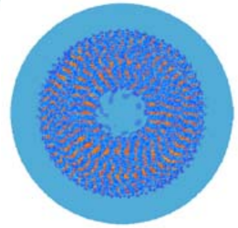
March 19, 2003

Gaithersburg, Maryland

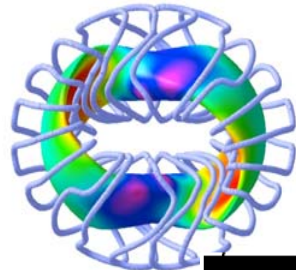
Strategic Goals of the ORNL Fusion Program



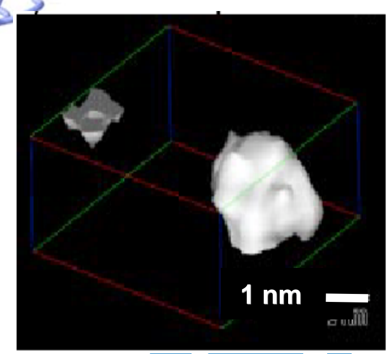
- **Toroidal Plasma Science Program**
  - **AT plasma scenarios; mass transport; wave heating**
  - **Address burning plasma issues in JET and DIII-D; long-pulse operation on Tore Supra**



- **Theory Program**
  - **Advancement of fundamental understanding of transport**
  - **Develop predictive capability for plasma heating, flow and current drive**
  - **Develop plasma modeling capability for advanced confinement concepts**



- **Concept Innovation**
  - **Development of compact stellarators: NCSX and QPS**
  - **Proof-of-principle experiment of the spherical torus: NSTX**

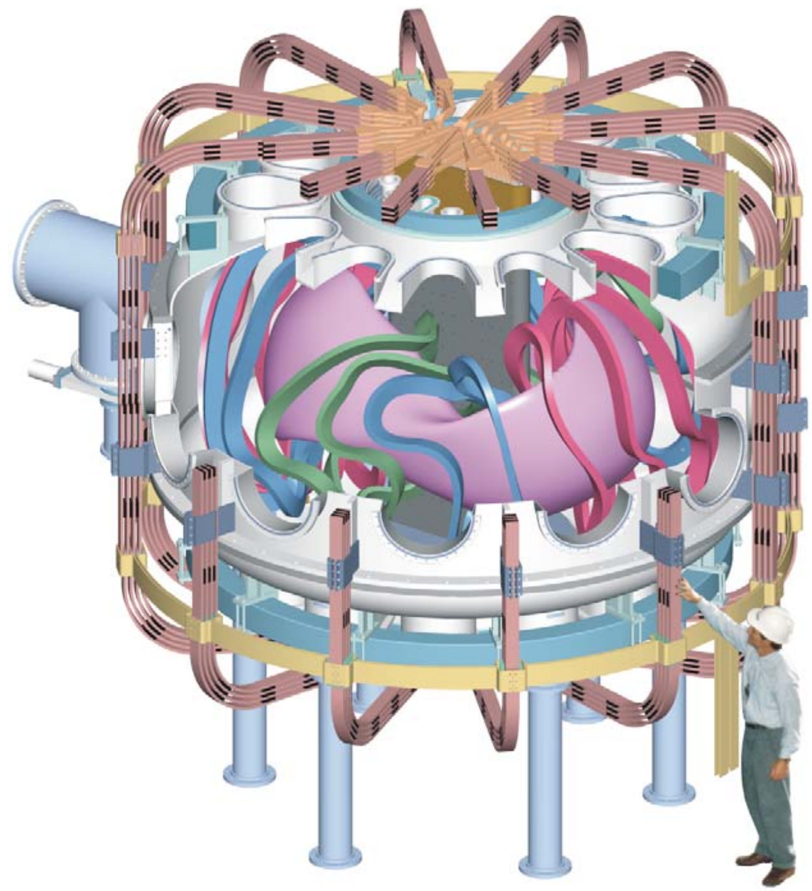


- **Enabling Science and Technology Research / NSO**
  - **Develop and test high-power, flexible, reliable ICRF systems**
  - **Develop inside-launch pellet injection and advanced fueling systems**
  - **Establish materials science base for advanced materials for fusion**
  - **Atomic physics data and diagnostics development**

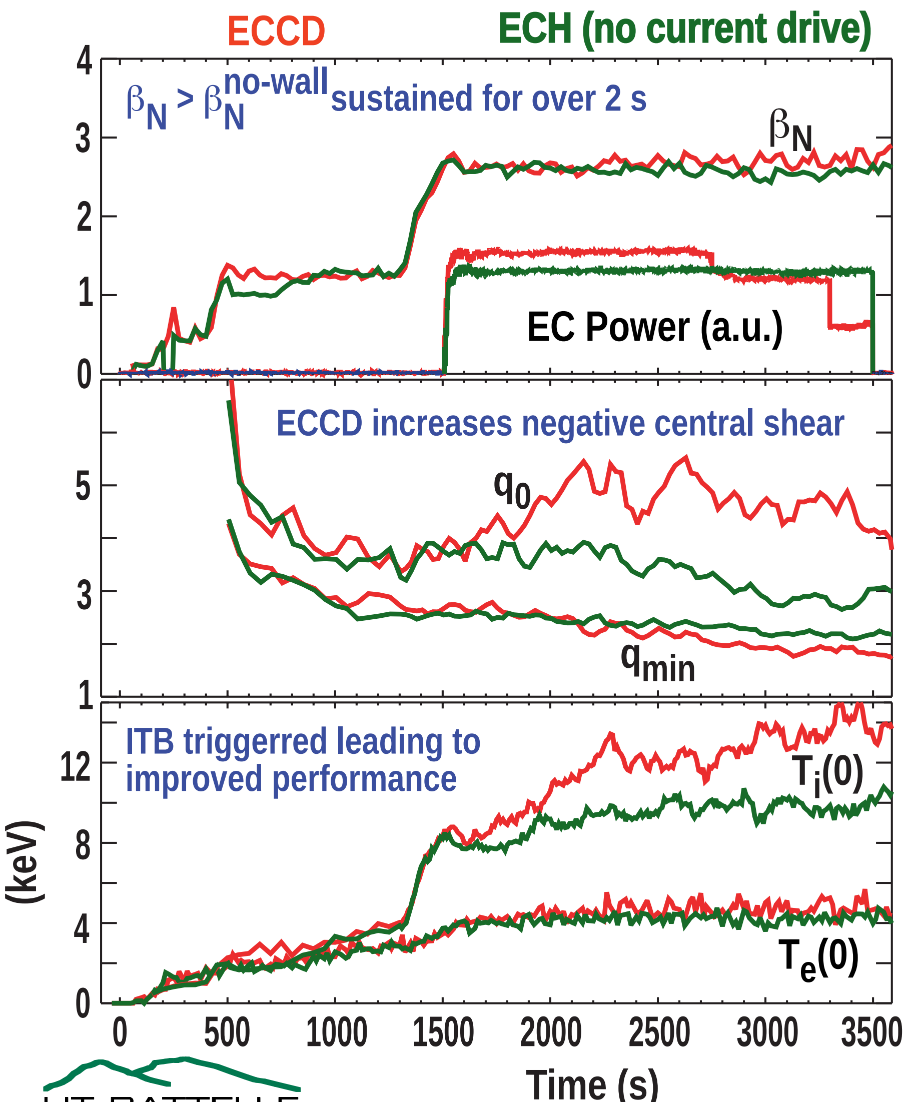
QPS and NCSX Compact Stellarators

"The Program Advisory Committee commends the QPS team on their excellent work on the physics and engineering design of the QPS experiment."

- **QPS Magnetic Configuration**
  - **improved neoclassical confinement by factor 5**
  - **Much wider range of configurations accessible for physics studies**
  - **Good magnetic surfaces in vacuum and at higher beta**
- **QPS Engineering design**
  - **Reduced modular coil complexity**
  - **Reduced coil current density 20%, increased plasma-coil distance 14%**
  - **Factor 2 smaller vacuum tank with VF coils moved outside the vacuum tank**
- **NCSX Development**
  - **Completed conceptual design of the stellarator core**

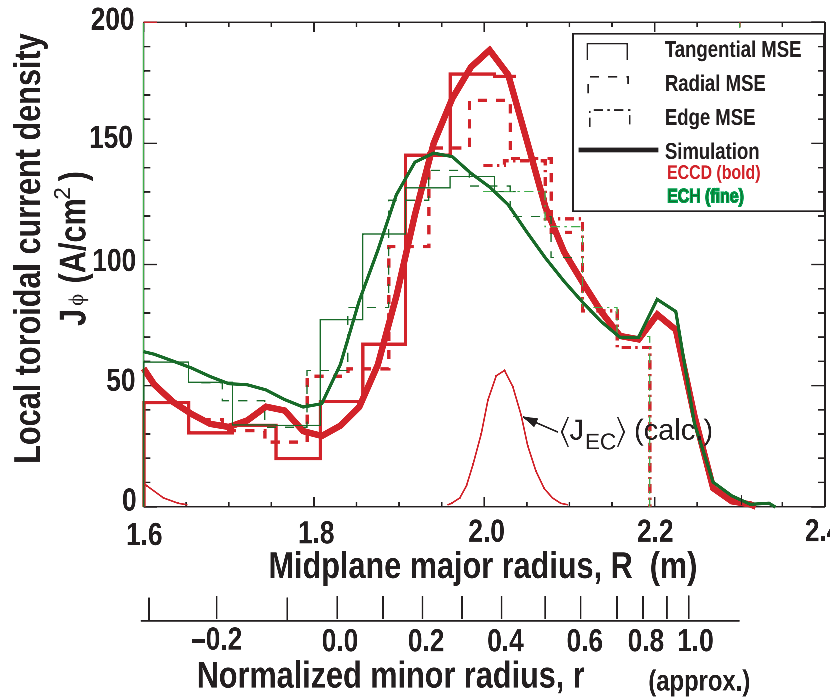


Experiments on DIII-D Have Demonstrated the Ability to Modify the Current Density Profile in a High-β Plasma



Murakami/Wade

- Predictive modeling guided experiment and aided in interpretation of results

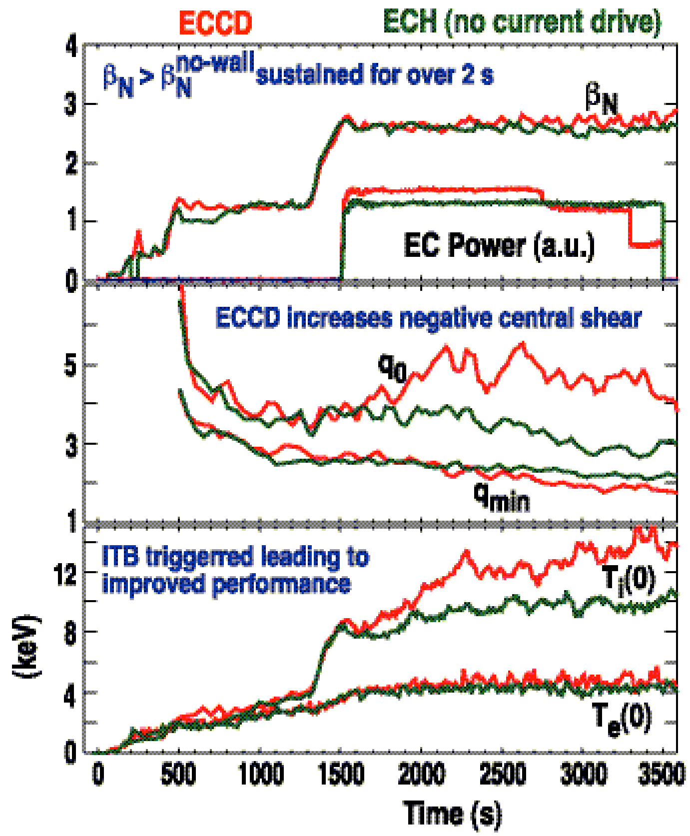


- Post-deadline talk at IAEA in Lyon and APS invited talk in Orlando

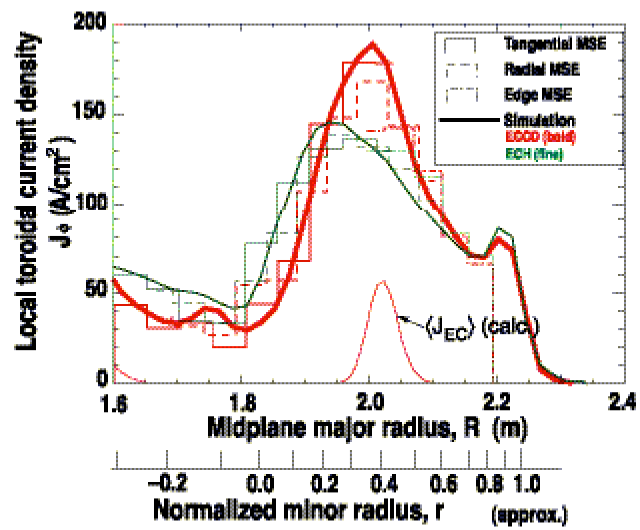
UT-BATTELLE BPM/2003 DIII-D NATIONAL FUSION FACILITY SAN DIEGO ornl

Experiments on DIII-D Have Demonstrated the Ability to Modify the Current Density Profile in a High-β Plasma

Murakami/Wade



- Predictive modeling guided experiment and aided in interpretation of results

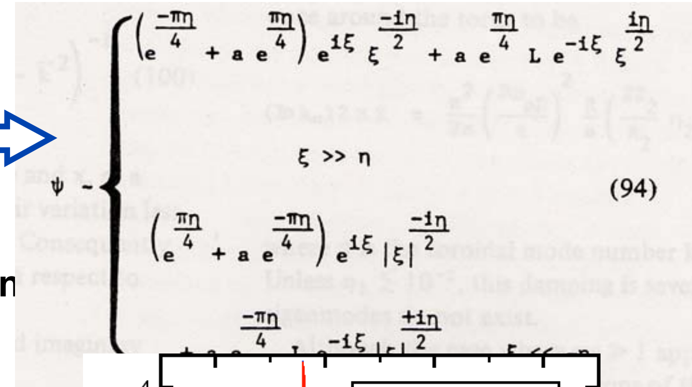


- Post-deadline talk at IAEA in Lyon and APS invited talk in Orlando

First Fully Resolved 2D Calculations of Conversion of Fast Waves to Short Wavelength Modes Were Obtained Within Our SciDAC Project

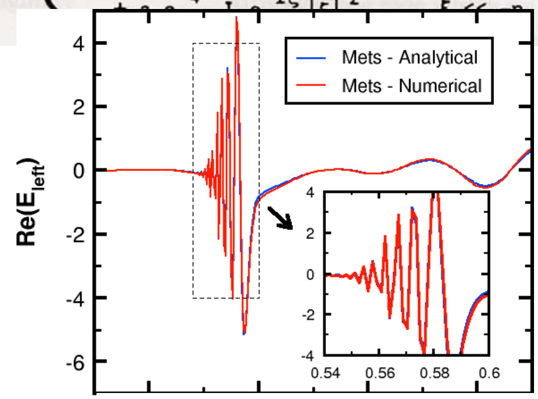
We have progressed from:

- Simple, approximate, analytic theory (F.W. Perkins, 1977)
  - Provided valuable paradigms for mode conversion
  - Indicated several conversions were possible
  - Did not give quantitative information for real 2D situation



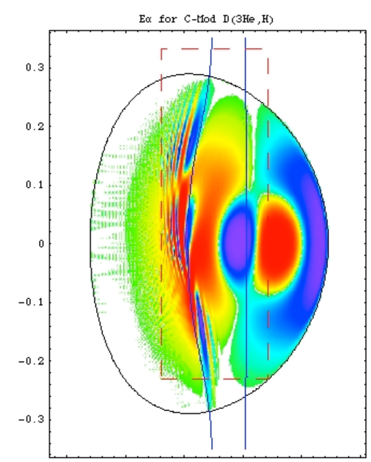
To:

- Numerical solutions in 1D (Smithe, 1997, Jaeger, 2000)
  - Verified analytic calculations with much more inclusive physics
  - Higher cyclotron harmonics, can treat short wavelengths

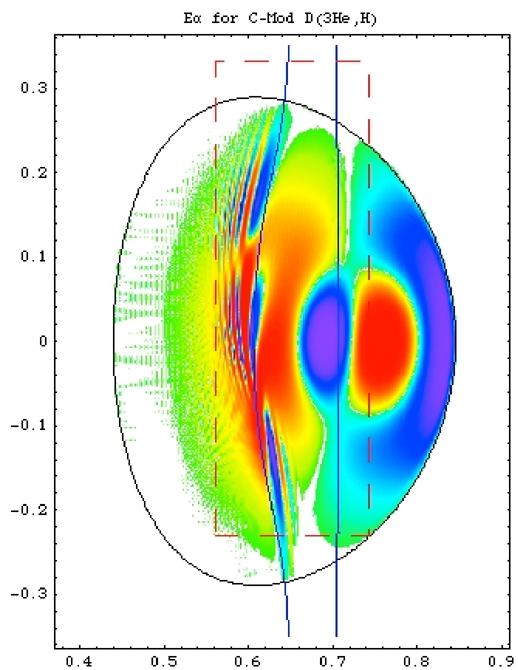


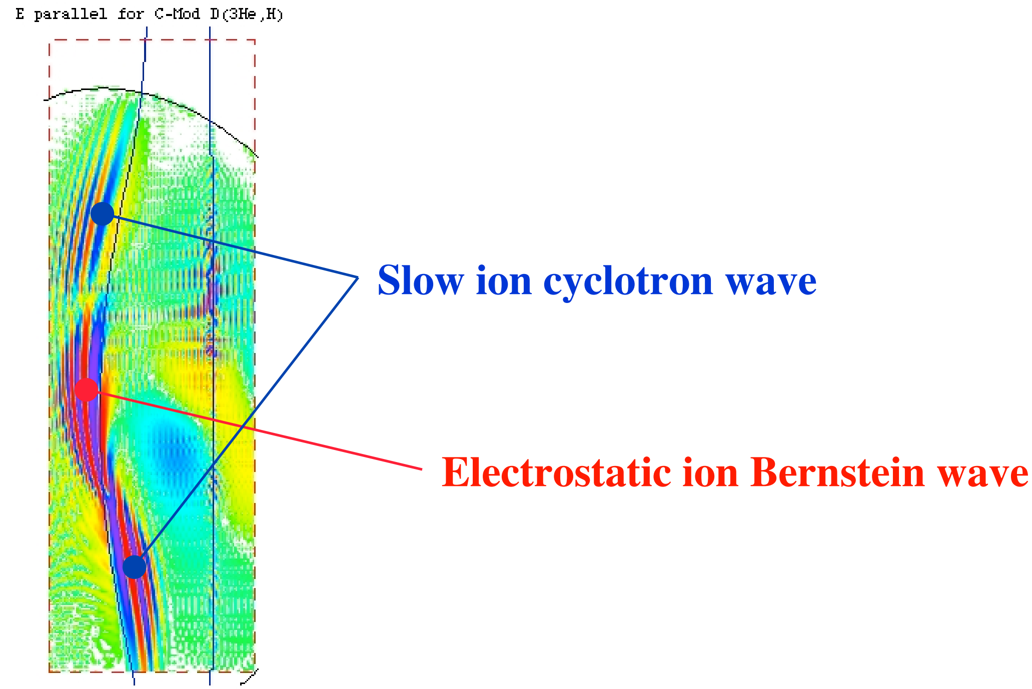
To:

- High-resolution solutions across the full plasma cross section (All Orders Spectral Algorithm AORSA2D, AORSA3D
  - Includes arbitrary cyclotron harmonics
  - Very short wavelength structures – limited by computer size and speed, not formulation
  - Full solution across plasma, geometrical representation of antenna



Surprise – We Find That Fast, Long Wavelength Electromagnetic Waves Can Be Converted More to Slow Electromagnetic Ion-cyclotron Waves Than Electrostatic Ion Bernstein Waves As Previously Expected





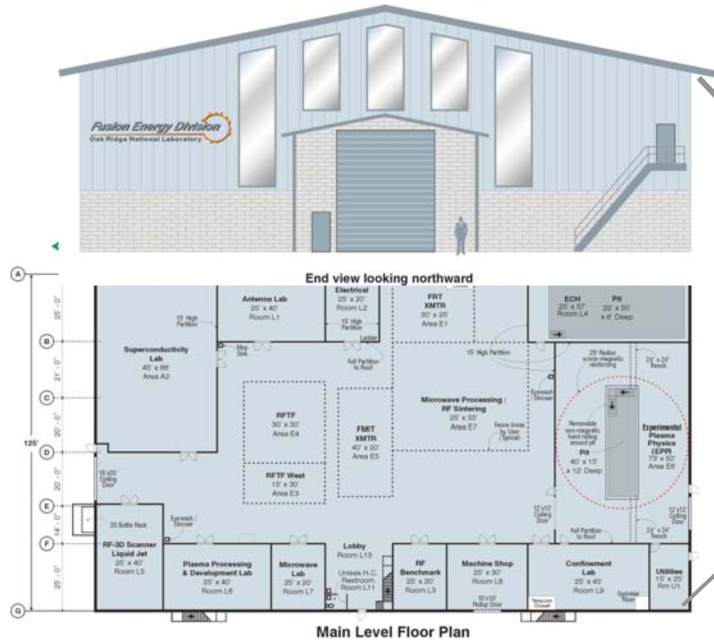
Blowup region

- **Previous 1D theory suggested that both conversions could occur, but gave no information about relative importance or actual field structure**
- **2D theory gives complete, quantitative picture**
- **Evidence of conversion to slow ion cyclotron waves seen experimentally on Alcator C-Mod at MIT**

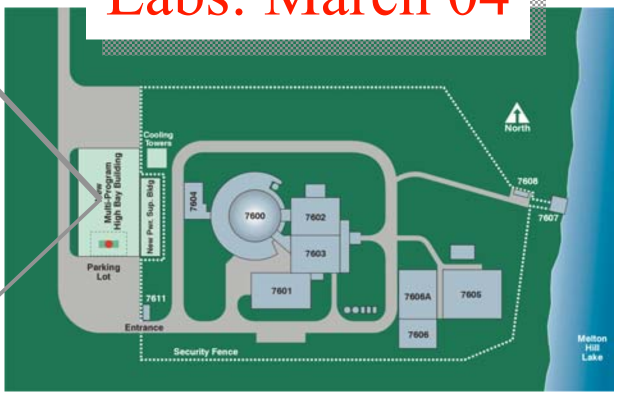
This can be practically important

- **Bernstein waves damp on electrons, can drive current**
- **Ion cyclotron waves damp on bulk ions, can drive plasma flow→ turbulence suppression**

Fusion Energy Division Is Getting a New Home Courtesy of the Laboratory



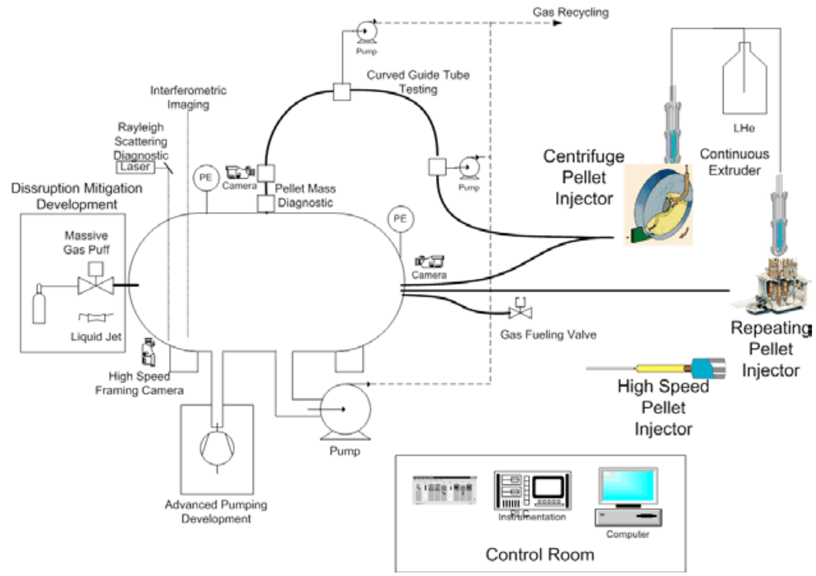
Labs: March 04



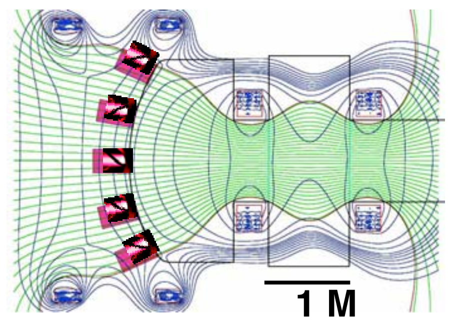
Offices and small research labs: Oct. 03

The New Research Facility Could House New Technology Test Beds for Domestic and Burning Plasma Program R&D

- **Plasma fueling test facility**
  - **Gas gun, centrifuge and high speed injector concepts**
  - **Realistic fuel throughputs**

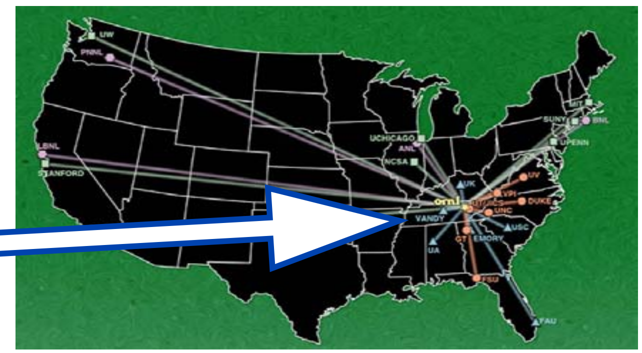


- **Radio frequency antenna test facility**
  - **Test antenna concepts under realistic edge plasma conditions**
    - **High density helicon plasma feed**



We Regard the Fusion Simulation Project (FSP) to Be Key to the Program – ORNL Would Be a Good Candidate to Host the Initiative

- **Strong fusion theory capability**
- **Strong computer science and applied capabilty –Large OASCR program**
- **Strong connection to university community through Joint Institute for Computer Science (JICS)**
- **New office and hardware infrastructure**
- **Unparalleled network infrastructure**
- **New MPP/vector architecture (Phoenix: Cray X1, 3.3TFlops) – Proposed to grow to 250 Tflops, Cray X2**

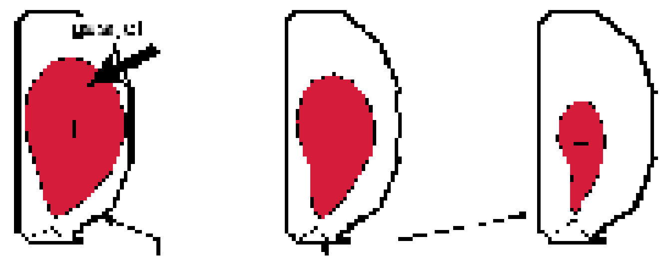


250 TF Cray X2

ORNL Contributes to Key Topics of Burning Plasmas

- **BPX Experiments on JET and Tore Supra**
  - **High-power antenna prototype**
  - **Helium diagnostics for DT operation**
  - **Fueling and heating scenarios for ITER**
  - **Long-pulse plasma scenarios (4 min discharge on Tore Supra)**

- **BPX Experiments on DIII-D**
  - **Scenario development**
  - **High-performance plasmas**
  - **ELM mitigation and effects on impurities**
  - **Disruption Mitigation**
  - **Long-pulse rf antenna replacement**



- **Theory and modeling**
  - **Advanced modeling of RF and fueling**
  - **Scenario Simulation**
  - **Leadership and broad participation in ITPA**

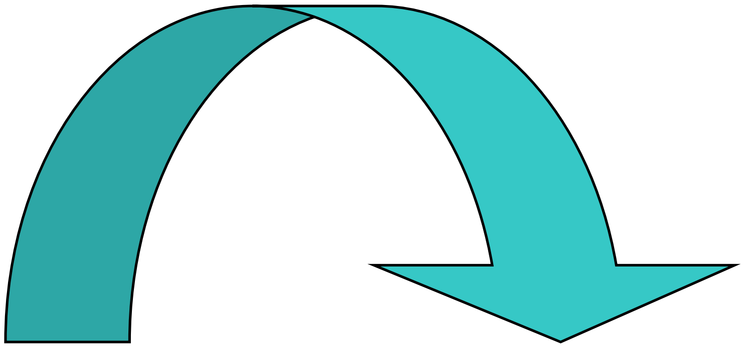
Budget Issues

Task	FY03	FY04-FY03	Incremental request	Description
QPS	1155	(209)	FY04 1000	Regains 5 months in fabricating an R&D coil
JET	93	+10 but	FY03 187 FY04 227	Increments needed for JET He diagnostic commitments
Theory	2489	(294-394)	FY04 810	3-D and edge physics for stell exp. and FSP FTCC evaluation and porting fusion codes for adv architecture
Plasma Tech	1573	(288)	FY04 288 FY04 215	288 correct error 215 for HPP tests
Fusion Tech	626	(626)		Loss of 2 FTE's are a concern
Atomic Physics	887	3		Flat budgets since 1996. Possible 1FTE impact
Move	350	650 but		New BA needed to place contracts and begin move

Budget Issues

- **Funding reductions delay QPS design and R&D** (=> J. Lyon's talk)
  - FY 2004 -- 18% reduction from FY 2003 and 73% reduction from QPS plan
  - Need increment at ORNL and PPPL to regain 5 months in R&D coil
  - $650k at ORNL + UTK and $350k at PPPL in FY 2004
- **Theory funding is 297k short for FY 2004 and FY2005 impacting:**
  - Modeling – participation in ITPA, preparation for FSP
  - 3D theory – equilibrium reconstruction for NCSX/QPS, preparation for FSP
  - FTCC - Evaluation and porting of fusion community codes to advanced architectures
- **JET He Diagnostics can not be delivered under the present budget**
  - shortfall: 187k for FY 2003, 227k for FY2004, 310k for 2005
- **Plasma Technologies**
  - ICRF technology has a shortfall of 125K for FY 2003, 288K for FY2004. Impacts 1 FTE and testing of "ITER-like" antennas and ITER-related R&D
- **Fusion Technologies**
  - Programs are zeroed out. Closeout costs and loss of 2 FTE's are a concern
- **Atomic Physics had flat budgets since FY 1996, can't keep up with cost of business**
  - shortfall 237 in FY 2004, 245 in FY 2005.
- **FED Move to X-10 site:**
  - new B/A needed to place contracts and begin move

Additional Viewgraphs on the ORNL Fusion Program



Plasma Theory - Directions for the Future

- **Major advanced computational initiative (community wide) for analysis of wave techniques of plasma heating and control**
  - 3D
  - high resolution - mode conversion in 2D/3D
  - high harmonic
  - distribution function consistency

- **Major scale-up in analysis capability for 3D systems**
  - 4D solution of drift kinetic equation
  - new approach to 3D equilibrium

- **Advancement of basic transport theory**
  - development of techniques for application of multifractal analysis to plasma turbulence studies
  - application of self-organized criticality (SOC) studies

- **Improvement in modeling/simulation capability for high bootstrap sytems - inclusion of plasma rotation, turbulent transport**
  - spherical torus
  - advanced tokamak
  - compact stellarator

Plans and Goals of ORNL Program on DIII-D

- **Confinement and stability studies**
  - **Scenario Development and modeling for the high bootstrap fraction AT regime**
  - **Hybrid regime**
  - **Sawtooth regime**
- **The FW system will benefit AT scenario development through:**
  - **Control of q_{min} and magnetic shear to optimize confinement and stability**
  - **Electron heating to increase off-axis ECCD**
- **Restart of the DIII-D Fast Wave system is a 3-way collaboration (GA, ORNL, PPPL)**
  - **FY2004: 285°(<1.5 MW @60MHz) & 0°(<1 MW @ 117 MHz) antenna operations**
  - **FY2005: 3 systems, 285°, 0°, and 180°(ABB2 converted by PPPL), available with < 4 MW**
  - **Incremental: Start design of a long-pulse "ITER- like" replacement for the 285°antenna**
- **Mass Transport**
  - **Additional 1.8-mm gun for HFS pellet fueling and ELM mitigation**
  - **ELM effects on impurity transport**

  Incremental
  - **Post-doc to continue the (discontinued) edge spectroscopic work**

NSTX Collaboration Highlights

- **RF Collaboration**
  - Current drive experiments conducted, with measurable loop voltage difference between co- and counter phasing
  - EBW detection antenna built and installed
  - Density profiles obtained regularly with the ORNL microwave reflectometer; fluctuation data frequency response improved to 500 kHz
  - ECH pre-ionization system maintained and routinely operated for breakdown
- **H-Mode and Plasma Boundary Physics**
  - Long pulse H-mode scenario developed with center stack gas fueling
  - Power threshold, ELM, and fueling studies initiated
  - Progress made in heat flux scaling and power balance studies (FY03 milestone)
- **Scenario Modeling**
  - Ion thermal transport anomaly investigated with NCLASS and FORCEBAL

ORNL International Collaborations Address Unique Issues That Can't Be Addressed In U.S. Machines

Main Themes:
- Impurity transport in highly radiating- and ELMing regimes
- Hydrogen isotope (T) and Helium pathways in tokamaks
- HFS pellet fueling
- Performance improvement by wave heating

- **JET:**
  - Measure hydrogen isotopes and rare gas impurities in the divertor; modeling of H,D,T pathways
  - Compare impurity transport/ELM effects in JET and DIII-D
  - HFS injection, pellet injector "in a suitcase", (T-injector)
  - High-power prototype rf antenna to achieve high performance plasmas
- **Tore Supra:**
  - Evaluate impurity transport in sustained AT / RI-mode scenarios
  - Investigate recycling and heat extraction in long-pulse operation
- **TEXTOR:**
  - Investigate helium and impurity transport in RI-mode and DED plasmas
- **ASDEX-U:**
  - Development of B2-EIRENE code for JET, DIII-D, etc
  - Study of basic rf breakdown scenarios
- **LHD:**
  - Study fast ion behavior and modeling in a large stellarator

UT-BATTELLE JET LHD NIFS Max-Planck-Institut für Plasmaphysik EURATOM Assoziation TORE SUPRA CEA-EURATOM ornl

Enabling Technology Highlights

Massive gas puff technology tested in experiments on DIII-D (ITER relevant)

High field side pellet fueling on DIII-D achieves high fueling efficiency

Compact stand-alone pellet injection system provides flexible plasma fueling. Initial test on MST

6 MW operation of NSTX ICRF system and real-time control of phase to vary current-drive efficiency

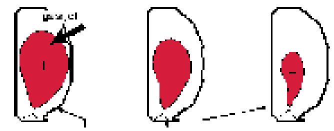
Fabricated high-power prototype antenna for JET-EP

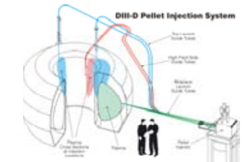
Initial EBW coupling measurements conducted on NSTX

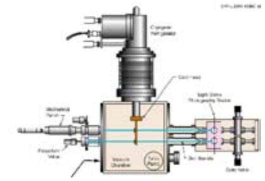
Successful comparison of experiment and modeling for a light ion helicon source (Physics of Plasmas, 09/02 M. D. Carter*, et al.)

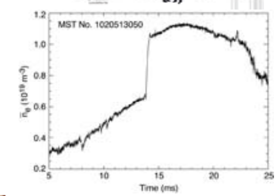
Technology applied on developing concepts (MST, Electric Tokamak, QPS, ALPS, APEX, IFE target fabrication)

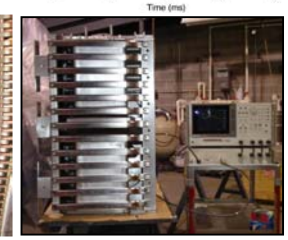
Plasma Science & Technology support for basic science and applications (Nanotube electron emission, high temperature superconductors, isotope separation, materials processing, wafer imaging)

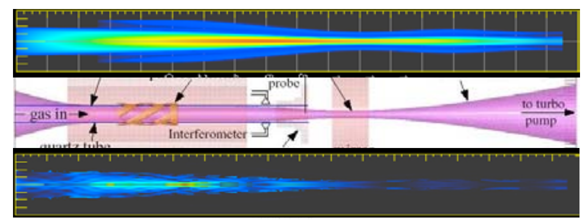


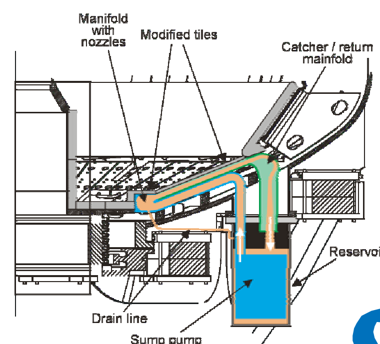


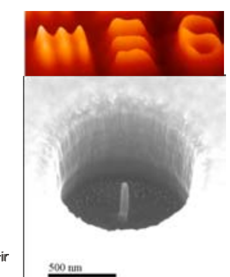






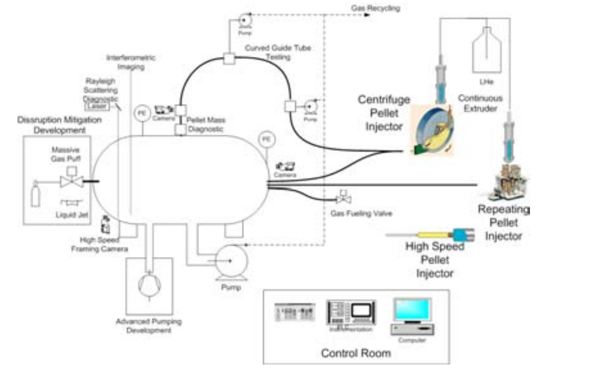




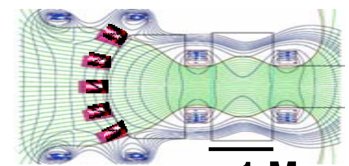


Technology Program Thrusts

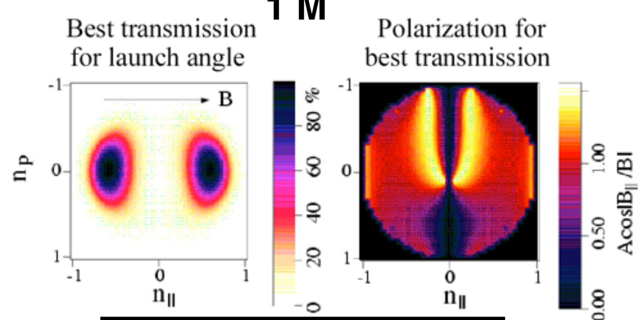
Fueling and pumping
- Test of hydrogen extruder with cryocooler
- Develop compact pellet injector for NSTX
- Design high-speed compact vertical injector for burning plasma proof-of-principle test on DIII-D or JET; (FIRE, ITER relevant)
- Upgrade test facilities and begin R&D for burning plasma device



ICRF Technology
- Evaluation of antenna and/or tuning upgrades for NSTX, C-Mod and DIII-D
- Instrument antennas to improve reliability and power handling
- Extended tests of the high power prototype ICRF antenna for JET-EP
- Tests of ITER like antennas on ET, Tore Supra and JET
- Upgrade facilities and begin R&D for burning plasma device



EBW Technology
- ECH/EBW current initiation on NSTX
- EBW heating and current drive on NSTX, MST and QPS



Plasma Science & Technology support for basic science and applications (Hydrogen storage, electron emission from nanotubes, carbon fiber processing, microwave melting of metals)

Enabling Technology Goals and Plans

- **Pellet fueling**
  - Investigate physics and technology of high-field-side pellet launch
  - Injector development in support of high-field-side launch on DIII-D, JET, Tore Supra, and LHD
  - Develop at ORNL and test on DIII-D a prototype disruption mitigation system
  - Develop compact fueling systems with flexible launch capability for initial applications on MST, NSTX, ET and NCSX
  - Upgrade facilities and begin R&D for burning plasma device

- **Wave heating and current drive**
  - Develop high power-density antennas that deliver increased power per port Design, build and test "ITER-like" antennas
  - Improve understanding of the physics of rf-plasma interactions, comparing code calculations to measurements on different experiments
  - Improve reliability and flexibility of ion-cyclotron systems:
    - reliable arc detection and localization
    - high power delivery into rapidly changing plasmas
    - arc / ELM discrimination
  - Develop real-time heating and current-drive control methods
  - Enhance efficacy of ICRF program via integration with the National facilities and through International collaborations
  - Upgrade facilities and begin R&D for burning plasma device

ORNL International Collaborations Provide Opportunities to Develop U.S. Technology

Main Themes: - Pellet fueling development
- ICRF technology development

- **JET:**
  - HFS injection, curved guide tube tests and fueling deposition analysis
  - Compact pellet injector "in a suitcase", T-injector
  - ICRF performance improvement by real time matching
- **LHD, W7-AS:**
  - Deep fueling for high β operation
  - ICRF heating in non-axisymmetric systems
- **ASDEX-U:**
  - Basic rf breakdown studies in a tokamak plasma
  - Next generation antenna design
- **TEXTOR**
  - HFS injection utilizing curved guide tubes

IPP Max-Planck-Institut für Plasmaphysik EURATOM Association

Atomic Physics for Fusion and Diagnostics

- **Experimental Atomic Physics**
  - Perform measurements of electron impact excitation cross sections for multicharged ions, and of electron impact dissociation cross sections for light hydrocarbon molecular ions
  - Initiate measurements of sputtering, desorption, and particle reflection for very low energy impact of H^+, D^+, and He^+ on fusion relevant wall materials
  - Perform measurements of very-low-energy electron capture by low charge state divertor ions and light hydrocarbon molecular ions
- **Data Center and Fusion Theory**
  - Continue CFADC bibliographic effort, making available atomic data on line, carrying out data production and collection projects, participation in IAEA Data Center Network, cooperation with NIFS data collection
  - Continue development of low-energy heavy particle cross section database, continue development of hidden crossings theory to ions/atoms and collisions in electromagnetic fields, respond to data needs of plasma science community
- **Diagnostics Development**
  - Design, develop, and evaluate wideband multichannel filter-bank receiver for alpha particle velocity distribution measurements

ORNL Advanced Fusion Materials Development

- **Reduced-activation ferritic steels**
  - Develop models of the flow & fracture behavior of irradiated steels (low T limit)
  - Microstructural analysis of helium trapping/migration (quantify high T limit)
  - Property measurements and structural analysis of new oxide-dispersion-strengthened steels (expand operating temperature limit to 800˚C)

- **Development of silicon carbide composite materials**
  - Generate knowledge base on the effects of neutron displacement damage on physical properties (develop operating temperature and dose limits)
  - Explore effects of high concentrations of helium (determine high T limit)
  - Apply state-of-the-art processing methods and advanced fibers

- **Development of V-Cr-Ti alloys**
  - Investigate viability of MHD insulators for V/Li system
  - Develop innovative joining techniques for V alloys
  - Develop comprehensive models of flow and fracture behavior of V-4Cr-4Ti based on HFIR irradiation data (quantify low T limit)
  - Determine creep rupture properties of V-4Cr-4Ti (determine high T limit)
  - Determine thermodynamics and kinetics of oxygen and hydrogen interactions in V-4Cr-4Ti (allowable O, H partial pressures)